Spring fires in a semimature trembling aspen stand in central Alberta

D. Quintilio, M.E. Alexander, and R.L. Ponto

Northwest Region • Information Report NOR-X-323

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Cover photo:
Leafless aspen stand in the spring, near Hondo, Alberta. (Photo courtesy of M. Maffey, Northern Forestry Centre, Edmonton, Alberta.)

93-00198/

SPRING FIRES IN A SEMIMATURE TREMBLING ASPEN STAND IN CENTRAL ALBERTA

D. Quintilio,[1] *M.E. Alexander,*[2] *and R.L. Ponto*[3]

INFORMATION REPORT NOR-X-323

FORESTRY CANADA
NORTHWEST REGION
NORTHERN FORESTRY CENTRE
1991

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Minister of Supply and Services Canada 1991
Catalogue No. Fo 46-12/323E
ISBN 0-662-19268-0
ISSN 0704-7673

This publication is available at no charge from:

Forestry Canada
Northwest Region
Northern Forestry Centre
5320 - 122 Street
Edmonton, Alberta
T6H 3S5

A microfiche edition of this publication may be purchased from:

Micromedia Ltd.
Place du Portage
165, Hôtel-de-Ville
Hull, Quebec
J8X 3X2

Printed in Canada

CANADIAN CATALOGUING IN PUBLICATION DATA

Quintilio, D.

Spring fires in a semimature trembling aspen stand
in Central Alberta

(Information report ; NOR-X-323)
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-19268-0
DSS cat. no. Fo46-12/1992

1. Forest fires – – Alberta – – Prevention and control.
2. Forest fires – – Research – – Alberta. 3. Aspen – –
Alberta. I. Alexander, Martin E. II. Ponto, R.L.
(Raymond Leonard). III. Northern Forestry Research
Centre (Canada). IV. Title. V. Series: Information
report (Northern Forestry Centre (Canada)) ; NOR-X-323.

SD420.7Q56 1992 634.9'618 C92-099561-6

This report has been printed on recycled paper.

Quintilio, D.; Alexander, M.E.; Ponto, R.L. 1991. *Spring fires in a semimature trembling aspen stand in central Alberta.* For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-323.

ABSTRACT

In a May 1972 study in central Alberta, thirteen 0.15-ha plots of semimature trembling aspen (*Populus tremuloides* Michx.) were burned experimentally under various conditions. The objective of the study was to provide new information on fire behavior and impact, with particular regard to aspen ecosystems. Fire data were documented for all plots, particularly head fire rates of spread and frontal fire intensities. The following August an assessment was made of the impact of burning on aspen overstory mortality and understory vegetation response: aspen suckering was minor after burning, but some species resprouted prolifically. In May 1978 two of the plots were jointly reburned, and, among other data, a 10-fold increase in fire intensity was documented, due largely to aspen mortality in 1972 and the subsequent increase in fuel load. The August survey that followed assessed the effects of the reburning, notably the virtual elimination of aspen after the combined fire treatments.

RÉSUMÉ

Lors d'une étude menée en mai 1972 dans le centre de l'Alberta, 13 parcelles de peupliers faux-trembles (*Populus tremuloides* Michx.), mesurant chacune 0,15 ha, ont été soumises à un brûlage expérimental sous diverses conditions. Cette étude avait pour objet de fournir de nouvelles informations sur le comportement et l'impact du feu, notamment dans les écosystèmes à peupliers faux-trembles. Des données sur le feu ont été recueillies pour toutes les parcelles, en particulier la vitesse de propagation à la tête de l'incendie et l'intensité du front des flammes. Au mois d'août suivant, on a procédé à une évaluation de l'impact du brûlage sur la mortalité de l'étage dominant et sur la réaction de la végétation du sous-étage: le drageonnage du peuplier faux-tremble était faible après le brûlage, alors que certaines espèces ont eu des repousses en quantité. En mai 1978, 2 des parcelles ont été en même temps l'objet d'un autre brûlage, et, entre autres données, l'intensité du feu a été notée comme 10 fois plus grande, à cause en grande partie de la mortalité du peuplier faux-tremble en 1972 et de l'augmentation qui a suivi dans la densité du combustible. Le relevé du mois d'août a évalué les effets du rebrûlage, en particulier l'élimination virtuelle du peuplier faux-tremble après les traitements au feu combinés.

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NOTE

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INTRODUCTION

In Alberta about 40% of productive forest land is dominated by trembling aspen (*Populus tremuloides* Michx.) (North 1976; Strong and Leggat 1981; Samoil and Turtle 1982). Aspen is easily killed by fire; after stand distrubance, however, the species pioneering capability enables it to compete very successfully through the production of adventitious root suckers. Therefore, although an individual aspen tree may be highly susceptible to damage by fire (Starker 1934), aspen as a vegetation type is extremely fire-resilient (Graham et al. 1963; Ahlgren and Ahlgren 1984; Perala 1990). Rowe (1983) has catergorized the trembling aspen as an "endurer." Many aspen stands in Alberta have originated after a fire has occurred, and it is generally accepted that fires of low or moderate intensity encourage suckering (Horton and Hopkins 1965; Maini and Horton 1966b; Sando 1972; Perala 1974b). Conversely, aspen suckering may be reduced by severe and/or repeated burning (Stoeckeler 1948; Buckman and Blankenship 1965; Perala 1974a). The ecological role of fire in aspen ecosystems has been recounted in several review papers (e.g., Brown 1985, 1985b; DeByle 1985; Jones and DeByle 1985; Rouse 1986).

Fires in undisturbed aspen stands are normally of low intensity. In fact, during the summer fire season (i.e., following leaf-out), pure healthy aspen stands are virtually impenetrable by fire, except under extreme burning conditions, especially when the stands cover sizable areas. The extent of their impenetrability, which makes them relatively effective fuelbreaks against wildfires (Johnson 1975; Fechner and Barrows 1976), is due to a number of weather and microclimatic factors, and to seasonal changes, each affecting the overall fire danger: reduced wind speed in the stand; shaded forest floor conditions; cooler temperatures; higher relative humidities; and the presence of live understory vegetation with very high moisture content following "green-up." In the western United States, however, numerous fuel-related factors appear to be responsible for the low flammability of aspen forests (Brown and Simmerman 1986; DeByle et al.1987).

The forest floor of an aspen stand immediately after spring snowmelt is in a matted condition, with cured surface vegetation and deciduous leaf litter. Before leaf-out this mat is directly exposed to the drying effects of wind and solar radiation, which increase fuel temperature and rapidly deplete fuel moisture (Van Wagner 1969a). Without rain, the weathered aspen leaves in the litter mat gradually begin to curl, resulting in a more favorable fuelbed for combustion and heat transfer. In Alberta, for example, these moderately severe, early season burning conditions can persist from snowmelt until the first week of June (Fig. 1).

In a quantitative sense, the range of potential fire spread (and fire intensity) during the period from snowmelt until leaf-out was not documented;

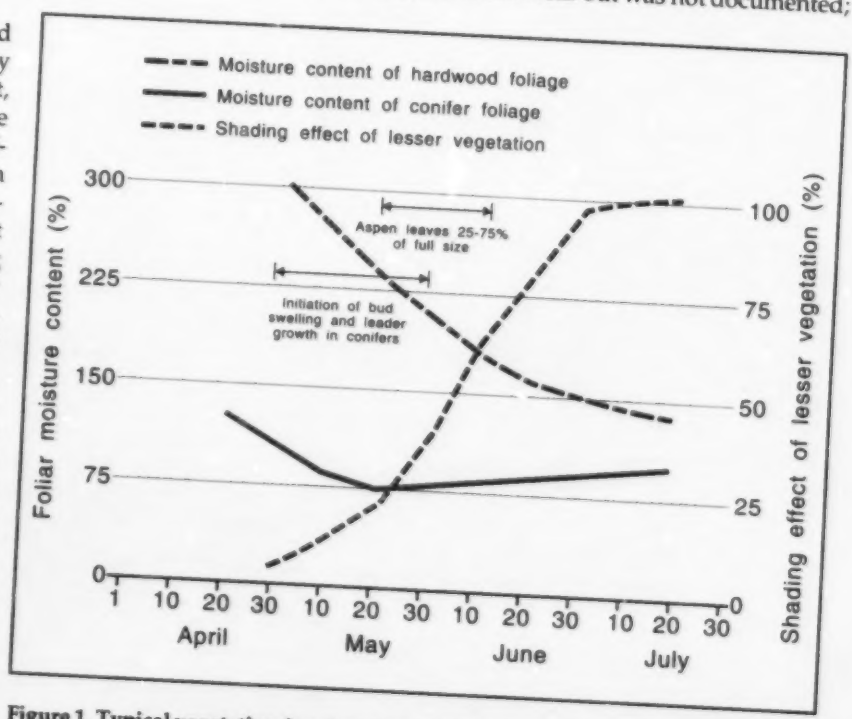

Figure 1. Typical vegetative development and foliar moisture content trends during the spring and early summer in central Alberta (after Kiil et al. 1977).

however, thirteen 0.15-ha plots were experimentally burned during May 1972 in central Alberta to determine the behavior, impact, and effects of fire in a semimature trembling aspen stand (Quintilio 1978). In August 1978, a 0.23-ha portion of the original study area was reburned (i.e., one-and-a-half plots); mortality of the aspen overstory and recovery of understory vegetation were monitored both before and after the 1978 reburn. The results of the 14 experimental fires are summarized in this report. The aspects of this study relating to fire behavior support continuing development of the Canadian Forest Fire Danger Rating System (Stocks et al. 1989; McAlpine et al. 1990).

DESCRIPTION OF STUDY AREA

Location

Geographically, the experimental burning site lay approximately 200 km north of Edmonton, Alberta (latitude 50°06′ N and longitude 114°08′ W), and about 6 km northwest of the town of Hondo, Alberta (legal description: NE Section 30, Range 2, Township 70, West of the Fifth Meridian) (Fig. 2). The actual study area was located within the boundaries of a fire research reserve established in the Slave Lake Forest during the early 1970s (Kiil and Quintilio 1971; Kiil et al. 1986).

Ecosystem

The details of the study area's ecosystem are as follows:

1. The study area was within the Boreal Mixedwood Forest Section (B.18a) according to Rowe (1972) and the Boreal Mixedwood Ecoregion (No. 8) according to Strong and Leggat (1981).

2. The stand typified the *Populus-Corylus* ecosystem (Kabzems et al. 1986).

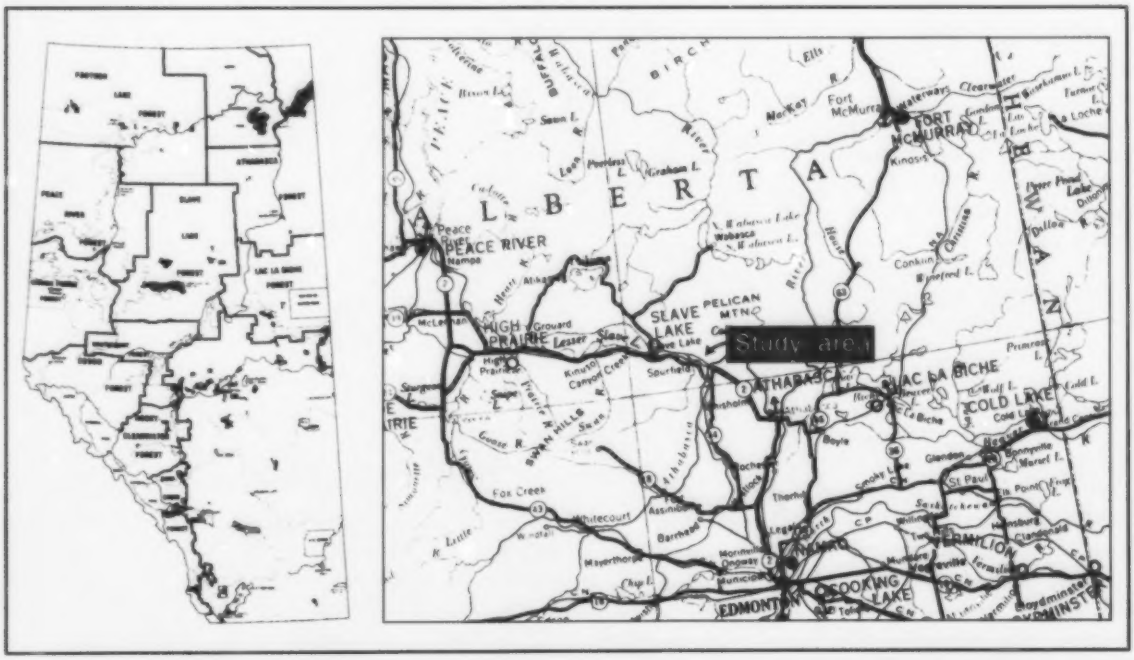

Figure 2. Geographical location of the experimental-burning study area in a semimature trembling aspen stand within the Slave Lake Forest near Hondo, Alberta.

3. The northern variant of the aspen forest at the Hondo study area was best described as Forest Cover Type 16 (aspen), as defined by the Society of American Foresters (Eyre 1980).

4. The study area was surrounded by open, grassed muskeg, which contained some black spruce (*Picea mariana* [Mill.] B.S.P.).

5. The site was well drained, and the mineral soil was a loamy sand underlain by deep layers of coarse and fine sand.

6. The area was situated at an elevation of 590 m above mean sea level (MSL).

7. The microtopography was strongly undulating, with a terrain slope of less than 10%.

For this study, burning plots were located in a nearly pure stand of semi-mature trembling aspen. The stand also consisted of scattered white spruce (*Picea glauca* [Moench] Voss) and jack pine (*Pinus banksiana* Lamb), and infrequent clumps of white birch (*Betula papyrifera* Marsh.). Understory tall shrubs included green alder (*Alnus crispa* [Ait.] Pursh), pin cherry (*Prunus pensylvanica* L.), and beaked hazel (*Corylus cornuta* Marsh.). Predominant herbs were twin-flower (*Linnaea borealis* ssp. *americana* [Forbes] Hult.), vetchling or pea vine (*Lathyrus ochroleucus* Hook.), wild sarsaparilla (*Aralia nudicaulis* L.), dewberry or running raspberry (*Rubus pubescens* Raf.), and bunchberry (*Cornus canadensis* L.). A more complete description of the understory species composition and phytosociological characteristics of the study area, as well as other vegetation worth noting, may be found in the section on fire impact and effects. Species' nomenclature used in this report follows Moss (1983).

METHODS

Plot Establishment

In April 1971 an area of approximately 228 × 236 m was selected in the trembling aspen stand; a 12-m-wide fire guard was then bulldozed around the perimeter, and all debris moved outside the area (Fig. 3). Eight primary blocks (each 45 × 100 m) within the area were isolated from each other by narrow strips (6 or 12 m wide) bulldozed down to mineral soil. Individual burning plots were later delineated with handlines; it is conceivable that, for this particular fuel type, the final plot size could have been determined just before ignition (Alexander and Quintilio 1990). Throughout the range of fire-weather conditions experienced during the study, each burning plot was one-third of a primary plot (i.e., 0.15 ha) and rectangular in shape. All burning plots were oriented with their long sides in a north-south direction. A permanent water dugout was constructed near the southwest corner of the study area (Fig. 3) to facilitate the use of pumps and a sprinkler system (Quintilio et al. 1971).

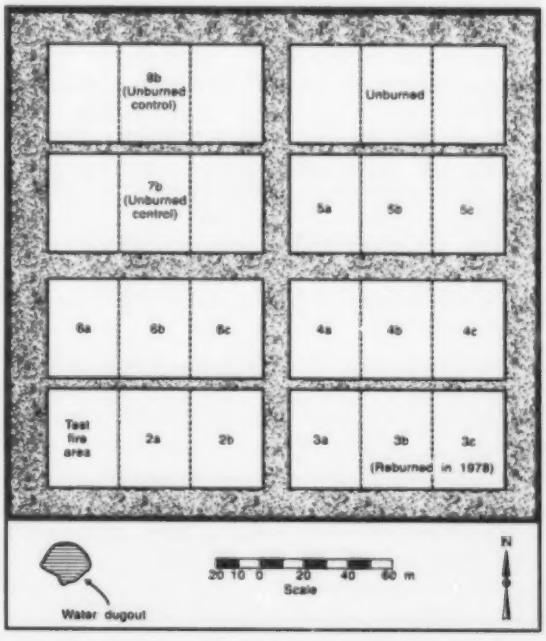

Figure 3. Layout of plots in the study area.

Fuel and Vegetation Assessments

The overstory in the stand was inventoried by primary units. The diameter at breast height (dbh) size classes of all live and dead tree stems were initially recorded in May 1971, using circular 0.04-ha fixed plots for reference during subsequent postfire mortality counts. Downed-dead woody surface fuels were inventoried by using the line intersect sampling method (Van Wagner 1968a) before and after burning. Understory vegetation weights were determined from 4 randomly clipped 1.0-m^2 quadrats per plot. The depth and weight of the organic layer were determined from 50 randomly located samples, 929 cm in size (30.48 × 30.48 cm), taken throughout the study area. The litter (L) layer was separated from the accumulation of fermentation (F) and humus (H) layers: the depth of the combined F and H layers was measured at the corners of the sample frame (it was not practical to demarcate separate F and H layers). Eight subsamples of the combined F and H layers were incinerated in a muffle furnace to determine the percentage of inorganic material. The thickness of the organic layer was measured at 160 points per plot. The depth of burn (DOB) (Merrill and Alexander 1987) was recorded at 50 to 150 point-sample locations in each of the burning plots, depending on the extent of fire coverage. Species composition and frequency, and the cover of understory shrubs and herbs were determined from 25 point-samples (Levy and Madden 1933) located in each surveyed plot.

Fire Weather and Fire Danger Measurements

Standard daily 1300 Mountain Daylight Time (MDT) fire weather observations were recorded in 1972 at Chisholm lookout tower, 10 km south of the burning site, and in 1978, at a temporary weather station that was 3 km south of the site (Appendix 1). The measurements taken included dry-bulb temperature, relative humidity (RH), 10-m open wind speed, and 24-hour accumulated rainfall (if any). The Canadian Forest Fire Weather Index (FWI) System components (Canadian Forestry Service 1984; Van Wagner 1987) were calculated daily for 15 days beginning on May 1 in 1972, and for 12 days beginning on April 24 in 1978 (Van Wagner and Pickett 1985). The standard fuel moisture code starting values were used (Turner and Lawson 1978; Canadian Forestry Service 1984). Wind speed and direction were continuously recorded within the stand at a height of 1.4 m during each experimental fire. Temperature and RH were recorded independently at a height of 1.2 m in an adjacent area of open exposure.

The relationship between wind velocity in the aspen forest and the standard meteorological measure of 10-m in the open was investigated separately. Two recording anemometers, one placed at a height of 1.4 m in an unburned plot and the other at 10 m in an adjacent exposure, were run simultaneously for a period of 52 days. A ratio factor was then derived from the information. Wind speed measured at 1.4 m in the stand during each experimental fire was adjusted, using this ratio factor, to approximate a 10-m open wind at the burning site (Quintilio et al. 1977).

Fuel Moisture Content Sampling

In both 1972 and 1978 a fire research documentation team obtained samples of the forest floor material (n = 2–6) for moisture content determinations before the ignition of each plot (fuel moisture content sampling of hardwood leaf litter is difficult in the spring when the litter is underlain with wet F and H layers). In 1978 downed-dead roundwood fuel and shrub samples (n = 3–5) were also taken. Samples were placed in metal soil sampling tins that were sealed with masking tape to prevent moisture loss (Fraser 1959) and then transported to the laboratory at the NoFC in Edmonton to be oven-dried at 100°C for 24 hours.

Experimental Burning Procedures

In April 1971, test fires were conducted in the southwest portion of the study area (Fig. 3) as a basis for developing the desired ignition pattern and fire behavior monitoring techniques that would ultimately be used in 1972 and 1978. The experimental fires were designed to spread as head fires from an established line source rather than from a single ignition point. The upwind edge of a designated burning plot was ignited by two hand-held drip torches. To ensure that the forward rate of advance had reached an equilibrium stage or "steady-state" (McAlpine 1988) for the prevailing burning conditions, the flame front was allowed to progress 10 m inside the stand before rate of spread measurements were begun. Average spread rates for each plot were determined by timing the flame

front progression in relation to a grid of coded stakes. In addition, metal tags that were inscribed with the elapsed time after ignition were dropped into the flame front (e.g., Peet 1967; Cheney 1971) during wind gusts in order to document maximum spread rates.

The objective of the study was to gather data which would ensure that the 1972 series of experimental fires was conducted during as wide a range of fire weather conditions as circumstances would permit. Burning was started soon after snow melt, when the fuel type was able to support a very slow-spreading fire; it continued until soon after leaf-out, at which time the moisture conditions within the stand prevented any further fires from being conducted.

For the experimental fires conducted in 1972, burning sequence was dependent on wind direction and hose requirements for the sprinkler units, which were positioned to wet down windrowed debris and generally keep mop-up efforts to a minimum. Alberta Forest Service (AFS) fire suppression crews operated the pumps and hose layout on all burning days.

RESULTS

Stand and Fuel Complex Attributes[1]

The research site was located in a 43-year-old (reference year: 1971) stand, which is shown in Fig. 4. Height and dbh of the trembling aspen stems averaged 13 m and 11 cm, respectively, and stand basal area averaged 29.38 ± 5.61 m^2/ha. Live and dead tree densities averaged 2802 ± 890 and 916 ± 581 stems/ha, respectively. Trembling aspen constituted 99% of the basal area and 98% of the stand density (Table 1).

The weight of the litter layer on a per unit area basis averaged 0.30 ± 0.09 kg/m. The depth of the F and H layers averaged 2.37 ± 0.36 cm, and the corresponding weight of the F and H layers on a per unit area basis, uncorrected for mineral content, averaged 2.57 ± 0.59 kg/m^2. Inorganic materials comprised approximately 59 ± 14% of the F and H layers by weight, according to the eight subsamples taken. Bulk density of the F and H layers averaged 0.0013 ± 0.0012 g/cm^3.

The woody fuels resting on the forest floor were meager when compared to many other forest cover types in Alberta (Singh 1987), averaging only 0.369 kg/m^2 for the study area as a whole. Consequently, the downed-dead woody fuels contributed little to fire behavior or the subsequent fire impact and effects of the 1972 fires.

Fire Weather and Fire Danger Conditions

In the spring of 1972 the winter snowpack had completely melted by April 28 in the study area.

Table 1. Original distribution (May 1971) of live and dead trembling aspen stems, by diameter size class, within the study area

Dbh[a] size class		Tree density[b] (stems/ha)	
Stem size (cm)	Stem class[c] (in.)	Live	Dead
2.5 - 5.0	1-2	25	315
5.0 - 7.5	2-3	306	428
7.5 -10.0	3-4	539	100
10.0 -12.5	4-5	656	42
12.5 -15.0	5-6	641	14
15.0 -17.5	6-7	409	12
17.5 -20.0	7-8	139	5
20.0 -22.5	8-9	34	0
22.5+	9+	17	0

[a] Dbh = Diameter at breast height.

[b] Density measured only for trembling aspen.

[c] Stems originally tallied by 1-inch dbh size classes.

[1] Where appropriate, both the mean ($\bar{X}$) and standard deviation (SD) are quoted together (e.g., 29.38 ± 5.61 m^2/ha).

Figure 4. Stand profiles in the study area. The upper photos were taken in February 1971, and the lower photo was taken in May 1972.

Starting May 9, 1972, burning continued until May 15. Thirteen plots were burned during the 7-day period, utilizing weather variations during that time (as integrated by the FWI System). In this study, the range of dry-bulb temperatures and of RH at the time of ignition was 13.9–23.9°C and 20–36% respectively (Table 2) (one fire was conducted in the morning with a RH of 54%). Average wind speeds measured at 1.4 m in the stand during the fires ranged from 0.8 to 4.2 km/h. The ratio of wind speed at 1.4 m in the stand to wind speed at a height of 10 m in the open on level terrain was determined to be 1:3.32. Equivalent wind velocities at 10 m in the open varied from 2.7 to 13.9 km/h (Table 2). The length of time after a significant (≥ 1.06 mm) rain varied from 3 to 9 days (Table 2).

The 1978 reburn consisted of the eastern half of Plot 3b and all of Plot 3c (Fig. 3); it took place on May 5. The fire weather and fire danger conditions associated with this experimental fire are presented in Table 2.

The 1972 fires and 1978 reburn were conducted under *low* to *high* fire-danger conditions, according to the class levels of the Fire Weather Index (FWI) component of the FWI System (Stocks et al. 1989), as originally described by Kiil et al. (1977) for Alberta. The Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI), and FWI associated with each experimental fire are summarized in Table 2. All plots were ignited between early afternoon and mid-afternoon (1335–1602 MDT), with one exception: Plot 5c was ignited at 1010 MDT. The FFMC for Plot 5c was estimated according to procedures outlined by Van Wagner (1972b) and Alexander (1982b). Included in Table 2 for comparative purposes is a May 1969 operational prescribed fire in a partially cut trembling aspen-white spruce stand[2] within the Lac La Biche Forest of east-central Alberta, as reported by Kiil (1970); the antecedent weather conditions are documented in the Appendix.

The present study represents the only attempt to date to conduct a series of experimental fires in the same aspen forest stand type on successive days during a single period of gradual drying conditions; however, most of the range in fire danger over the 7-day study period, as reflected in the ISI and FWI, was attributable to the variations in wind speed. In the FWI System, the heavier fuel moisture indicators varied over a narrow range, as reflected in the 19-point range in the DMC and BUI, and the 33-point range in the DC. Fine dead fuel moisture (indicated by the FFMC) covered most of the normal range where fire activity can be expected (i.e., from around 84 to about 93). Test fires ignited on May 7 and 8 in 1972 failed to sustain themselves at, respectively, FFMCs of 70 and 85 and ISIs of 0.5 and 2.0 (i.e., with no wind). All remaining fires spread uniformly over the entire plot; this suggested that an ISI of between 2.0 and 2.5 represents a threshold condition for sustained fire spread in the leafless aspen fuel type.

Fuel Moisture Contents

For the 1972 experimental fires, the actual sampled moisture content (MC) values of the fine dead surface fuels (i.e., the L layer) ranged from 8.9 to 14.4% (Table 3). These MCs were comparable to those previously reported for relatively similar weather conditions (Kiil 1970; Sando 1972; Alexander and Sando 1989). Van Wagner (1965) reported an MC of 6% for aspen leaf litter in association with a minimum RH of 16% and maximum air temperature of 29.5°C. The average MC for the combined F and H layers during the 7-day length of the study in 1972 was 128%, which is very similar to the very high MCs for duff measured on other aspen sites in the spring (Jarvis and Tucker 1968; Kiil and Grigel 1969; Johnston 1981; Johnston and Woodard 1985).

In 1978 the MCs of the downed-dead roundwood fuels on the reburn plot(s) were as follows:

Diameter (cm)	% MC
<1.0	9.0
<2.5	11.2

In 1978 the MCs of woody fuels that were 7.5 cm and 15 cm in diameter varied considerably, i.e.,

[2] Selective logging of merchantable white spruce took place in the early 1950s. The dominants in the residual stand were 85 years old, with an average height of 23 m. The hardwoods constituted 96% of stand density (1161 stems/ha) and 77% of the basal area (22.5 m^2/ha), respectively).

Table 2. Fire weather observations and fire danger indexes associated with the fourteen experimental fires conducted in the study area, arranged in order of increasing head fire rate of spread

Experimental fire plot number	Time of burning			Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind		Days after rain[b]	Canadian Forest Fire Weather Index System components[a]					
	Calendar date	Hour (MDT) Start	Hour (MDT) End			Speed (km/h)	Direction (from)		FFMC	DMC	DC	ISI	BUI	FWI
5c	13.05.72	1010	1058	15.6	54	2.7	WSW	7	84.7	23	45	2.3	23	4
6c	14.05.72	1354	1430	19.4	22	10.1	NNW	8	92.4	31	57	10.0	31	18
6c	15.05.72	1335	1405	13.9	32	9.1	SE	9	91.2	33	62	8.0	33	15
2b	09.05.72	1525	1604	22.2	20	2.7	SSE	3	91.7	14	29	6.3	14	8
5a	12.05.72	1404	1429	17.1	36	8.5	NNW	6	91.2	23	45	7.8	23	12
5b	12.05.72	1450	1518	19.4	27	7.5	NW	6	91.7	24	46	8.0	24	13
2a	09.05.72	1400	1430	23.3	25	6.4	SSE	3	91.3	14	30	7.1	14	9
3a	10.05.72	1420	1436	23.3	25	13.9	SSW	4	92.4	18	35	12.1	18	15
3c	10.05.72	1602	1614	23.3	24	5.3	SSW	4	92.4	18	35	7.9	18	11
4c	11.05.72	1529	1553	22.8	26	9.6	NW	5	92.1	21	41	9.4	21	14
4a	11.05.72	1407	1422	22.8	24	11.7	SSW	5	92.5	21	41	11.0	21	15
4b	11.05.72	1455	1506	23.9	22	13.3	WNW	5	93.1	21	41	13.0	21	18
3b	10.05.72	1500	1515	21.7	23	12.8	WSW	4	92.5	17	25	11.6	17	15
3b & c[c]	05.05.78	1430	1450	15.5	20	6.6	WNW	6	91.9	29	53	7.9	29	14
ADK[d]	16.05.69	1300	1800	14.2	25	17.0	NW	10	90.3	33	69	10.5	33	19

[a] The three fuel moisture codes and three fire behavior indexes comprising the Canadian Forest Fire Weather Index (FWI) System are defined below (from Canadian Forestry Service 1984):
Fine Fuel Moisture Code (FFMC) - A numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel.
Duff Moisture Code (DMC) - A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-sized woody material.
Drought Code (DC) - A numerical rating of the average moisture content of deep, compact, organic layers. This code is a useful indicator of seasonal drought effects on forest fuels, and amount of smouldering in deep duff layers and large bogs.
Initial Spread Index (ISI) - A numerical rating of the expected rate of fire spread; it combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel.
Buildup Index (BUI) - A numerical rating of the total amount of fuel available for combustion; it combines DMC and DC.
Fire Weather Index (FWI) - A numerical rating of fire intensity; it combines ISI and BUI. It is suitable as a general index of fire danger throughout the forested areas of Canada.

[b] Amount greater than 0.6 mm.

[c] Plots reburned in 1978.

[d] Adapted from Kiil (1970).

Table 3. Fuel moisture conditions and the impact of burning on the forest floor associated with the fourteen experimental fires conducted in the study area, arranged in order of increasing head fire rate of spread

Experimental fire plot number	Moisture content (%) L layer[a] (oven-dry weight basis)	Moisture content (%) F and H layers[b] (oven-dry weight basis)	Depth of burn (cm)	Forest floor reduction (%)
5c	—[c]	—[c]	2.15	47
6a	14.4	73	0.84	28
6b	9.4	91	0.81	26
2b	9.1	100	1.16	24
5a	11.8	167	1.84	40
5b	—[d]	—[d]	1.71	37
2a	11.0	156	1.13	28
3a	8.9	161	1.60	39
3c	13.4	86	1.37	34
4c	10.6	204	1.82	43
4a	10.2	156	2.15	51
4b	—[d]	—[d]	1.88	45
3b	—[d]	—[d]	1.36	33
3b&c[e]	11.2	84	3.45	76
ADK[f]	10.5	—[c]	3.30	75

[a] Litter (L) layer.

[b] Fermentation (F) and Humus (H) layers.

[c] Samples were not taken.

[d] Samples were taken shortly before or after ignition, on an adjacent plot.

[e] Plots reburned in 1978.

[f] Adapted from Kiil (1970).

11–31% and 15–104%, respectively. The MCs associated with the shrub stems above ground on the 1978 return plot(s) are given below:

Species	% MC
Green alder	112
Beaked hazel	151
Prickly rose	84
Huckleberry	114

These high MC values are typical for live understory vegetation (Loomis et al. 1979; Brown et al. 1989).

Fire Behavior Characteristics

Rate of Spread

Although most of the 13 experimental fires carried out in 1972 were conducted over a wide range of fire weather conditions (as indicated by the ISI component of the FWI System) (Figs. 5 and 6; Table 2), variation in forward spread rates was small in an absolute sense (Figs. 5 and 6; Table 4). Fire spread was extremely sensitive to changes in wind velocity, surface fuel arrangement, and microtopography. Head fire rate of spread (ROS) varied from *slow* at 0.28 m/min (Plot 5c) during the initial experimental fire (the first one to sustain itself following ignition) to *moderately slow* at 2.51 m/min (Plot 3b) during the most vigorous fire, according to the terminology and ROS classification of Alexander and Lanoville (1989). Maximum spread rates observed were 4.4 m/min. Previous studies of similar fuel types documented maximum spread rates of up to 15 m/min (Kiil 1970; Sando 1972; Alexander and Sando 1989).

The simple linear correlation coefficient (r) between the head fire ROS and the ISI (Fig. 5) is 0.672 (significant at the 1% probability level) for the 13 experimental fire observations obtained from the 1972 burning. A variety of equation forms that link head fire ROS to wind or to wind and fine fuel moisture can be found in the fire behavior prediction literature (e.g., Rothermel 1972; Cheney 1981; Van Wagner 1987). Three of the more commonly used equations were employed in this study to derive relationships between the ISI and head fire

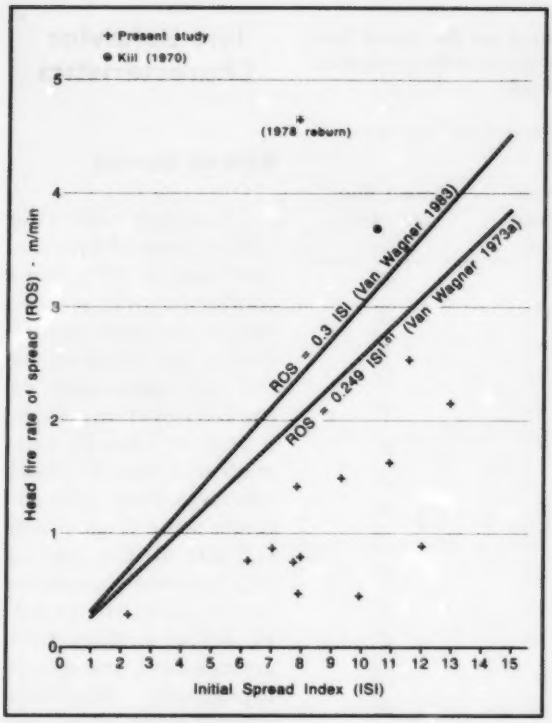
+ Present study
● Kiil (1970)
(1978 reburn)
ROS = 0.3 ISI (Van Wagner 1983)
ROS = 0.249 ISI^1.5 (Van Wagner 1973a)
Head fire rate of spread (ROS) - m/min
Initial Spread Index (ISI)

Figure 5. Thirteen experimental fires conducted in the study area in 1972, plotted as head fire rate of spread (ROS) versus Initial Spread Index (ISI). Existing ISI-ROS relationships for leafless aspen stands are included for comparison with results from the present study.

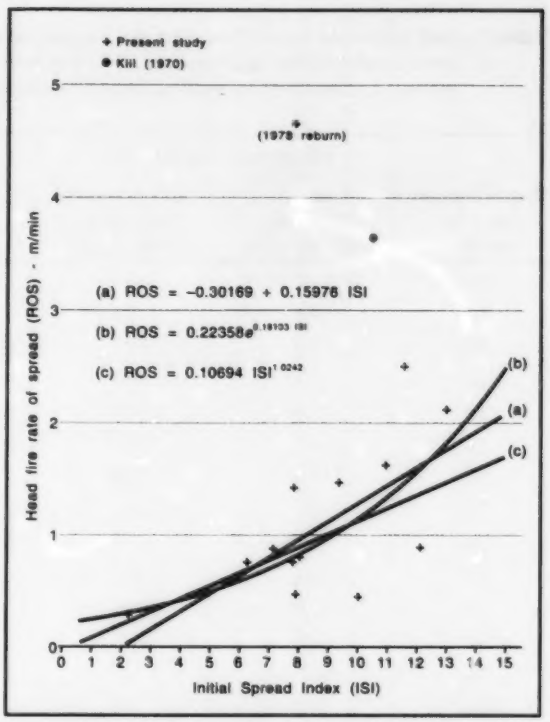
+ Present study
● Kiil (1970)
(1978 reburn)
(a) ROS = −0.30169 + 0.15976 ISI
(b) ROS = 0.22358e^0.16103 ISI
(c) ROS = 0.10694 ISI^1.0242
Head fire rate of spread (ROS) - m/min
Initial Spread Index (ISI)

Figure 6. Head fire rate of spread (ROS) as a function of the Initial Spread Index (ISI), according to three commonly used equation forms based on the thirteen experimental fires conducted in the study area in 1972. The plotted ISI-ROS data points are included for comparative purposes. The 1978 reburn and Kiil (1970) fires were not included in the regression analyses.

ROS. As graphically illustrated in Figure 6, the three regression equation forms are the linear, exponential, and power functions:

[1] $ROS = -0.30169 + 0.15976(ISI)$
with $r^2 = 0.45$, and $s_{y \cdot x} = 0.52$

[2] $ROS = 0.22358e^{0.16103(ISI)}$
with $r^2 = 0.51$, and $s_{y \cdot x} = 0.47$

[3] $ROS = 0.10694(ISI)^{1.0242}$
with $r^2 = 0.50$, and $s_{y \cdot x} = 0.47$

where ROS = head fire ROS (m/min). The coefficient of determination (r^2) values for the three regression equations are also given, as are the standard errors of the estimates ($s_{y \cdot x}$), which are significant at the 0.02, 0.007, and 0.006 probability levels, respectively.

Van Wagner's (1973, 1983) two equations, as presented in Figure 6, were published before the introduction of the interim edition of the Canadian Forest Fire Behavior Prediction System in 1984. These equations were based on a limited data set (six fires), and both equations generally tend to overpredict head fire ROS, as noted by Alexander and Sando (1989).

Fuel Consumption

During the series of 13 experimental fires carried out in 1972, the quantity of fuel consumed ranged from 0.177 kg/m^2 to 0.557 kg/m^2 ($\bar{X}$ = 0.347 kg/m^2). Correlations were poor between fuel consumption and the DMC, BUI, and MC of the

Table 4. Fuel consumption data and fire behavior characteristics associated with the fourteen experimental fires conducted in the study area, arranged in order of increasing head fire rate of spread

Experimental fire plot number	Fuel consumption[a] (kg/m^2)	Energy per unit area[b] (kJ/m^2)	Head fire rate of spread (m/min)	Frontal fire intensity (kW/m)
5c	0.177	3 214	0.28	15
6a	0.122	2 266	0.45	17
6b	0.117	2 298	0.47	18
2b	0.263	4 800	0.75	60
5a	0.307	5 680	0.75	71
5b	0.300	5 532	0.77	71
2a	0.274	5 034	0.87	73
3a	0.305	5 591	0.88	82
3c	0.507	9 319	1.41	219
4c	0.535	9 851	1.48	243
4a	0.557	10 259	1.62	277
4b	0.539	9 944	2.13	353
3b	0.507	9 323	2.51	390
3b&c[c]	3.402	57 261	4.60	4 392
ADK[d]	0.587	9 525	3.66	581

[a] Includes leaf litter, cured surface vegetation, downed-dead woody surface fuels, and the F and H layers.

[b] Numerically equal to the product of the low heat of combustion and amount of fuel consumed (Van Wagner 1978). A low heat of combustion value of 18 700 kJ/kg was used and reduced for fuel moisture content equivalent to 24 kJ/kg per moisture content percentage point (Alexander 1982a).

[c] Plots reburned in 1978.

[d] Adapted from Kiil (1970).

combined F and H layers, due largely to the lack of fuel involvement in the combustion process that resulted from the very high MCs in the lower forest floor layers. The degree of fuel consumption appeared to be more closely related to the preburn fuel load, and, to a lesser extent, the FFMC. However, the fact that the BUI averaged only 21 for all of the burning days, with a comparatively narrow total range of 14–33, undoubtedly limited the possible variation in fuel consumed.

Frontal Fire Intensity

In the 1972 series of experimental fires, flame heights ranged from 0.1 to 1.0 m (Fig. 7). This is typical for leafless aspen stands (Wright and Bailey 1982). Frontal fire intensities of 15–390 kW/m (Table 4) were calculated (cf. Alexander 1982a) on the basis of Byram's (1959) formula:

$$[4]\quad I = \frac{Hwr}{60}$$

where I = frontal fire intensity (kW/m), H = fuel low heat of combustion (kJ/kg), w = weight of fuel consumed in the active combustion zone (kg/m^2), and r = linear rate of fire spread (m/min).

All of the 1972 experimental fires would be considered to have a *fairly easy* difficulty of control rating (I < 500 kW/m) from the standpoint of frontal fire intensity (Alexander and Lanoville 1989). The fire behavior characteristics chart or nomogram (Alexander, Stocks and Lawson 1991; Alexander, Stocks, Lawson and McAlpine 1991) is useful for interpreting the behavior of free-burning forest fires with different rates of spread and varying degrees of fuel consumption, but similar frontal fire intensities (Fig. 8). Fires that are plotted in bands of equal frontal fire intensity successively farther from the origin are, in turn, progressively more severe.

As shown in Figures 5 and 6, the average head fire ROS of the 1978 reburn was 4.6 m/min—nearly double the average head fire ROS of the most vigorous 1972 fires. The frontal fire intensity of the 1978 reburn (Fig. 9) was calculated to be 4392 kW/m. This figure is equal to that of a high-intensity surface fire or an intermittent crown fire in a conifer forest stand (Quintilio et al. 1977; Alexander and De Groot 1988; Alexander and Lanoville 1989). When compared to the most intense 1972 fires, the 10-fold increase in frontal fire intensity of the 1978 reburn was due mainly to a substantial increase in the surface fuel load that resulted from aspen mortality

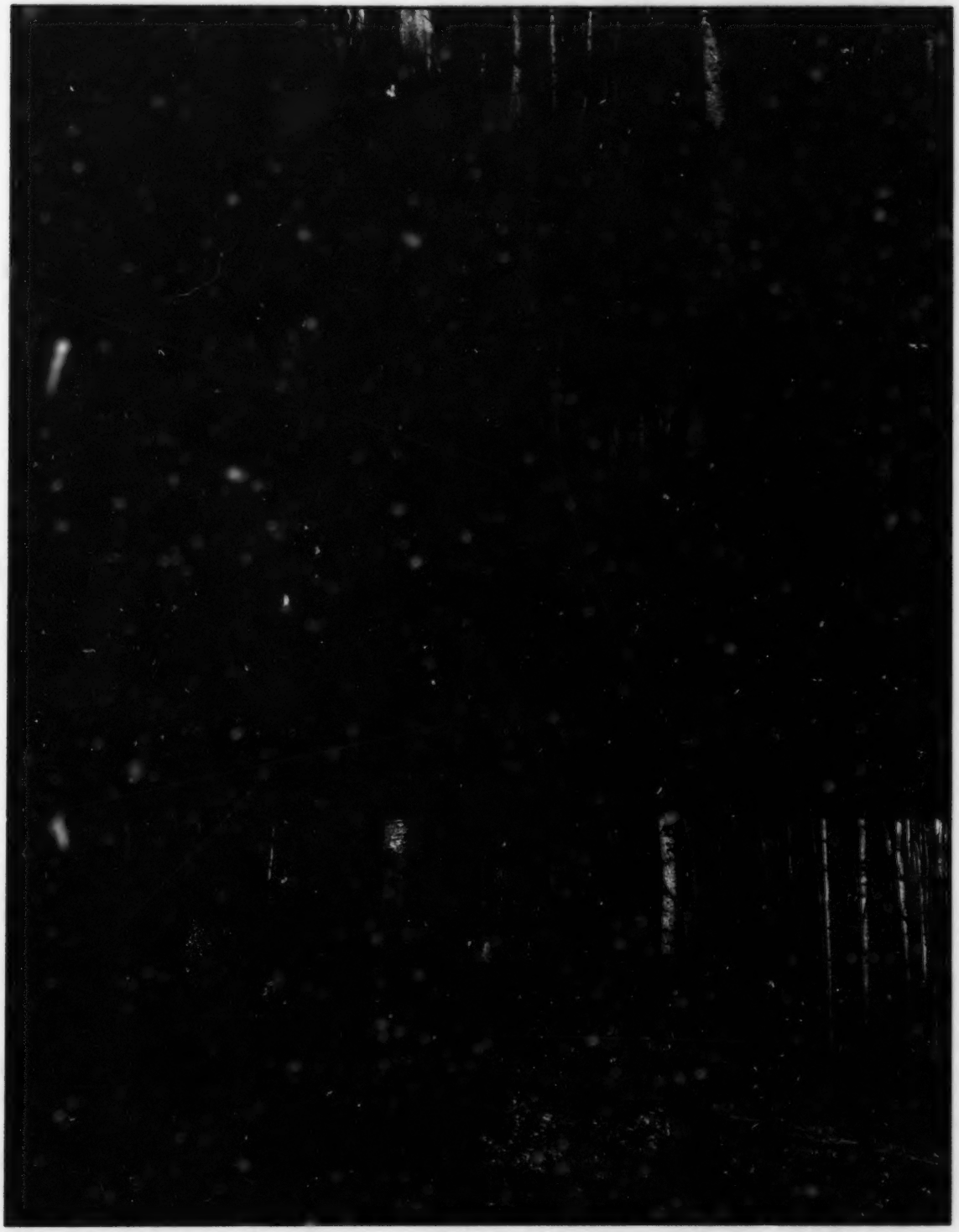

Figure 7. Flame front of low to moderately vigorous surface head fires during experimental burning in the study area in May 1972.

after the earlier fires in 1972. The degree of fuel consumption that was experienced on the 1978 reburn plot was found to be similar to that reported by Perala (1974b) for a partially cut aspen stand (Alexander 1982c): although the head fire ROS was not quite as great, the frontal fire intensity was certainly comparable (Fig. 8).

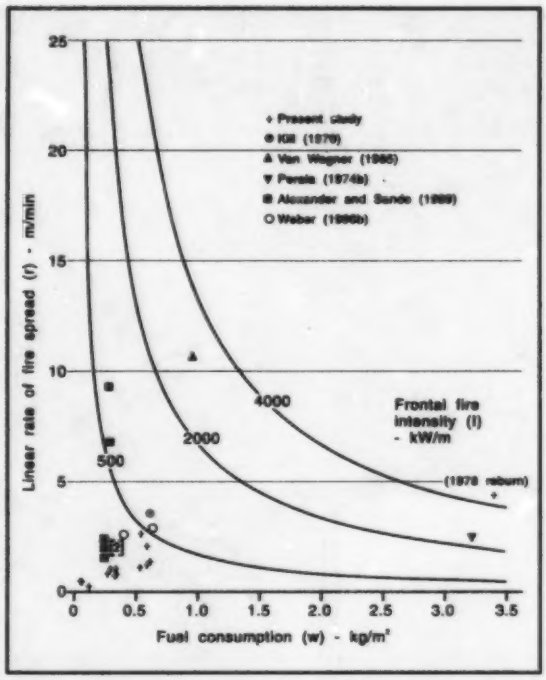

Figure 8. Head fire rate of spread and fuel consumption plotted in relation to four distinct levels of frontal fire intensity for the fourteen experimental fires conducted in the study area (net heat of combustion equaled 18 000 kJ/kg). Other experimental fires and wildfires in similar deciduous fuel complexes in the leafless state are included for comparison with results from the present study.

Fire Impact and Effects

Fuel Depletion

The average preburn L-layer depth for all the 1972 burning plots was 4.10 ± 0.51 cm. The 1972 burns reduced the litter layer by 37 ± 8%, which corresponded to a 1.53 ± 0.45 cm depth of burn (Table 3). Fuel consumption was low, consisting mainly of cured surface vegetation (0.43 kg/m^2), the previous year's leaf litter (0.104 ± 0.024 kg/m^2), and a small amount of woody surface fuels (0.200 ± 0.151 kg/m^2). Total fuel consumption averaged 0.347 ± 0.163 kg/m^2. The May 1978 reburn of Plots 3b and 3c consumed all the surface litter accumulation (0.188 kg/m^2) of those plots, a portion of the combined F and H layers (0.218 kg/m^2), and 58% of the total woody surface fuels (2.996 kg/m^2) located there.

Tree Mortality

A 27–30% strip cruise (by area) of the overstory in Blocks 3, 4, and 5 (Fig. 3) was completed in September 1976. In addition, control areas of 18 × 18 m quadrats (0.03 ha) were laid out in Plots 7b and 8b (Fig. 3) to survey natural tree mortality. The overstory stems in the May 1978 reburn plot(s) were sampled in late July, after the fire. The fire-induced tree mortality is summarized in Table 5, in which the natural mortality of live aspen stems is represented by the unburned controls (or analogues). The figures indicate that fires in the low-intensity class (<100 kW/m) had little or no effect on the aspen overstory. For moderately intense fires (~200 to 400 kW/m), tree mortality was a strong inverse function of stem diameter.

The 1978 postfire survey of the reburn area indicated almost complete mortality of the aspen overstory (Fig. 9). The moderately heavy accumulation of downed-dead woody fuels resulted not only in higher fire intensities but also in longer burn-out times that produced greater bole heating (Burrows 1987) and downward heat transfer to the rooting zone (Shearer 1975; Frandsen and Ryan 1986). This, in turn, contributed to the high degree of tree mortality experienced in the 1978 reburn.

Understory Vegetation Response

Understory vegetation cover and frequency data are presented in Table 6 for the postfire condition of the 1978 reburn plots (3b and 3c), the postfire condition of Plots 3a and 3b burned in 1972, and the unburned control or analogue. Following the May 1978 reburn, the August 1978 vegetation survey of Plots 3b and 3c showed a decline in the growth of trembling aspen, green alder, and beaked hazel, but an increase in bluejoint or marsh reed grass, dewberry or running raspberry, fireweed or great willow-herb, wild sarsaparilla, vetchling or pea vine, and wild vetch.

Figure 9. Before, during, and after the 1978 reburning of two experimental plots burned in the study area in 1972. The preburn and fire action photos were taken on May 5, 1978; the postburn photos were taken in late September 1978.

Table 5. Mortality of trembling aspen stems associated with the fourteen experimental fires conducted in the study area in 1972 and 1978

Dbh[a] size class		Tree mortality (%)					
		Moderate-intensity fires		Low-intensity fires	1978 reburn		
Stem size (cm)	Stem class[b] (in.)	Block 3c	Block 4	Block 5	Plots 3b&c	Unburned controls	ADK[d]
2.5- 5.0	1-2	67	0	100	100	100	98
5.0- 7.5	2-3	91	100	81	100	54	91
7.5-10.0	3-4	73	100	34	100	3	72
10.0-12.5	4-5	35	89	17	100	2	73
12.5-15.0	5-6	30	68	10	100	0	48 total
15.0-17.5	6-7	14	52	3	100	0	
17.5-20.0	7-8	15	24	3	95	0	
20.0-22.5	8-9	0	0	0	90	0	
22.5+	9+	0	0	0	90	0	
All size classes		45	68	29	97	15	86[e]

[a] Dbh = Diameter at breast height.

[b] Stems originally tallied by 1-inch dbh size classes.

[c] Experimental fire plot number 3a should actually be characterized as a low-intensity fire (Table 4) and is probably responsible for the apparent anomally evident in stem mortality of the 2.4–5.0 cm dbh size class.

[d] Adapted from Kiil (1970) and unpublished data on file with the Fire Management Research Project at Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

[e] No mortality was recorded in trees of more than 40.6 cm (16 in.) dbh.

DISCUSSION

Conditions under aspen stands are favorable for the decomposition of litter: the leaves are not particularly resistant to decay, and stand density is generally low enough to permit adequate precipitation and sunlight to reach the ground. As a result, the accumulation of forest floor material in aspen and other northern hardwood forests is usually light (Loomis 1975). The depths, weights, bulk densities, and inorganic contents of the individual and collective layers of the forest floor in the Hondo study area were similar to those measured at other locations in Alberta (Kiil and Grigel 1969; Kiil 1970; Kiil and Quintilio 1971; Kiil 1974), Ontario (Van Wagner 1970; Weber 1990a, 1990b, 1991a, 1991b), and the Lake States region of the U.S. (Alway and Kittredge 1933; Sando 1972; Alban 1974; Loomis 1977; Roussopoulos 1978; Beyerhelm and Sando 1982; Perala and Alban 1982; Simard et al. 1983; Ruark and Bockheim 1988).

The 1.4-m stand/10-m open wind speed ration of 1:3.32 is in remarkably good agreement with the ratios reported by Norum (1983) and Rothermel (1983) for leafless hardwood fuel complexes. In contrast, the 1.4-m stand/10-m open wind speed ratios for clear-cut jack pine slash (Chrosciewicz 1975) and black spruce–lichen woodlands (Alexander, Stocks and Lawson 1991) are 1:1.6 and 1:2.2, respectively.

Bailey (1978a, 1978b) has pointed out that prescribed burning in the aspen forest during the spring is not usually successful above an RH range of 35–40%, and may well be limited at an RH above 50%, depending on air temperature, wind velocity, and recent rainfall history. For safe and effective use of fire in leafless aspen stands, Bailey (1988) has recommended that prescribed burns be conducted 8–10 drying days following snowmelt, when the air temperature is at least 18°C, the RH is less than 30%,

Table 6. Characteristics of the understory vegetation within the experimental burning study area in August 1978

Species composition[a]		Plots 3b&c: 1978 reburn			Plots 3a&b: 1972 burns			Plots 7b & 8b: unburned controls		
Scientific name and authority	Common name	Frequency (%)	Cover (%)	PV[b] index	Frequency (%)	Cover (%)	PV index	Frequency (%)	Cover (%)	PV index
Corylus cornuta Marsh.	beaked hazel	4	4.0	8.0	16	31.2	124.8	48	61.2	424.0
Campanula rotundifolia L.	bluebell or harebell	12	1.6	5.5	—[c]	—	—	—	—	—
Vaccinium myrtilloides Michx.	blueberry	4	0.8	1.6	4	0.8	1.6	16	4.0	16.0
Calamagrostis canadensis (Michx.) Beauv.	bluejoint or marsh reed grass	48	7.2	49.9	44	13.2	87.6	8	2.4	6.8
Vaccinium vitis-idaea L. *minus* (Lodd.) Hult.	bog cranberry or cow-berry	—	—	—	4	1.6	3.2	—	—	—
Cornus canadensis L.	bunchberry	64	12.0	96.0	76	18.0	156.9	72	19.2	162.9
Prunus virginiana L.	choke cherry	—	—	—	12	6.4	22.2	24	4.8	23.5
Rubus pubescens Raf.	dewberry or running raspberry	64	13.6	108.8	40	8.0	50.6	40	7.2	45.5
Epilobium angustilolium L.	fireweed or great willow-herb	80	23.2	207.5	32	9.2	52.0	8	2.4	6.8
Alnus crispa (Ait.) Pursh	green alder	4	0.4	0.8	20	20.8	93.0	28	16.8	88.9
Agrostis scabra Willd.	hair or tickle grass	20	2.4	10.7	28	5.6	29.6	8	1.2	3.4
Equisetum palustre L.	horsetail or scouring rush	8	1.2	3.4	4	0.4	0.8	8	0.8	2.3
Aster ciliolatus Lindl.	Lindley's aster	—	—	—	4	0.4	0.8	—	—	—
Viburnum edule (Michx.) Raf.	low-bush cranberry or mooseberry	20	4.8	21.5	4	0.4	0.8	20	3.6	16.1
Galium boreale L.	northern bedstraw	20	3.2	14.3	20	8.0	35.8	8	1.2	3.4
Orthilia secunda (L.) House	one-sided wintergreen	8	1.2	3.4	4	0.8	1.6	12	1.6	5.5
Petasites palmatus (Ait.) A. Gray.	palmate-leaved coltsfoot	—	—	—	8	1.6	4.5	—	—	—
Prunus pensylvanica L.f.	pin cherry	—	—	—	—	—	—	20	8.4	37.6
Rosa acicularis Lindl.	prickly rose	60	16.0	123.9	84	30.0	275.0	56	20.4	152.7
Amelanchier alnifolia Nutt.	saskatoon	4	1.6	3.2	—	—	—	20	2.4	10.7
Aster conspicuus Lindl.	showy aster	16	3.2	12.8	12	2.8	9.7	—	—	—
Symphoricarpos albus (L.) Blake	snowberry	4	0.4	0.8	12	1.6	5.5	20	4.0	17.9

Mertensia paniculata (Ait.) G. Don.	tall mertensia	8	4.0	11.3	—	—	—	—	—	—
Populus tremuloides Michx.	trembling aspen	20	6.0	26.8	24	9.6	47.0	—	—	—
Linnaea borealis L. ssp. *americana* (Forbes) Hult.	twin-flower	12	1.2	4.2	16	2.8	11.2	40	6.8	43.0
Lonicera dioica L. var. *glaucescens* (Rydb.) Butters	twining honeysuckle	12	1.6	5.5	4	0.4	0.8	4	0.4	0.8
Lathyrus ochroleucus Hook.	vetchling or pea vine	68	30.8	254.0	44	10.0	66.3	—	—	—
Viola canadensis L.	western Canada violet	—	—	—	—	—	—	4	0.4	0.8
Maianthemum canadense Desf.	wild lily-of-the-valley	8	0.8	2.3	16	1.6	6.4	40	5.2	32.9
Rubus idaeus L.	wild red raspberry	12	2.0	6.9	16	5.2	20.8	8	2.0	5.7
Aralia nudicaulis L.	wild sarsaparilla	72	14.8	125.6	56	14.0	104.8	56	11.2	83.8
Fragaria virginiana Duchesne ssp. *glauca* (S. Watts.) Staudt.	wild strawberry	4	1.2	2.4	20	2.8	12.5	4	1.2	2.4
Vicia americana Muhl.	wild vetch	44	14.4	95.5	4	0.4	0.8	—	—	—

[a] Species also present but not recorded: fairy-bells (*Disporum trachycarpum* [S. Wats.] B. & H.); red and white baneberry (*Actaea rubra* [Ait.] Willd.); cut-leaved anemone (*Anemone multifida* Poir.); veiny meadow rue (*Thalictrum venulosum* Trel.); crane's-bill (*Geranium bicknellii* Britt.); and buckbrush or wolfberry (*Symphoricarpos occidentalis* Hook.).

[b] PV = Prominence Value; according to Beal's formula (1960), PV = Cover $\times \sqrt{\text{Frequency}}$.

[c] Species not present.

and 10-m open winds are 9–35 km/h. The ISI component of the FWI System takes all of these factors into account (i.e., temperature, RH, wind speed, and rain) and in a single number integrates the effects of several consecutive days of wind and weather on fine fuel flammability and fire spread. Bailey (1988) formulated his guidelines on the basis of more than 20 years of prescribed fire research experience in the aspen parklands of central Alberta (Bailey 1978a), where the surface fuels were modified by cattle grazing.

The duff or F and H layers in an aspen stand dry slowly and retain considerable moisture unless subjected to a prolonged dry spell (Jarvis and Tucker 1968). The MCs for the F and H layers listed in Table 3 should be interpreted as the natural variation in forest floor MCs, rather than as actual daily changes. It should be noted that Johnston (1981) found that, on the basis of 32 random samples taken on a single spring day, the average duff MC in his 4-ha study area was 120%, but MCs ranged from 67% to 210%.

According to the fuel consumption-BUI relationship given by Martell et al. (1984), the amount of fuel expected to be consumed would be 0.18–0.37 kg/m^2, based on a BUI level of 14–33. It is worth noting that when the Gwatkin Lake Fire in eastern Ontario occurred on May 7, 1964, it was reported to have consumed 0.976 kg/m^2 of aspen-type fuels (Van Wagner 1965), with a BUI level of 54 (Weber et al. 1987). Kiil and Grigel (1969) estimated that during the major run of the Lesser Slave Lake Fire in central Alberta on May 23, 1968, the surface fuel consumption in aspen stands was about 2.0 kg/m^2; this occurred with a BUI level of at least 70 (Alexander 1983). MacCracken and Viereck (1990) observed that the organic layer was "burned off at many sites, exposing mineral soil" (the sites presumably included 70-year-old aspen stands), following the major run of the Rosie Creek Fire near Fairbanks, Alaska, on June 2, 1983, at which time the BUI was probably about 114 (Alexander 1991).

When burning conditions are taken into account, the fire behavior of the present study is consistent with that of other documented experimental fires in aspen stands in Alberta (Kiil 1970; Johnston 1981; Johnston and Woodard 1985), Ontario (Van Wagner 1973, 1975; Alexander 1982a; Weber 1990a, 1990b, 1991a, 1991b), the Lake States region of the U.S. (Alexander and Sando 1989), and the western U.S. (Brown and DeByle 1983, 1987, 1989; Smith 1983; Smith et al. 1983). Head fire spread rates and frontal fire intensities seldom exceed 12 m/min or 3350 kW/m (Van Wagner 1968b). The light surface fuel loads and lack of ladder fuels contribute to this relatively low fire hazard condition, a fact that is reflected in various rating schemes (e.g., Chrosciewicz 1983; Kabzems et al. 1986). The amount of fuel potentially available for combustion in the trembling aspen fuel type is also limited because the duff layer typically exhibits very high MCs during the narrow "burning window" in the spring (before leaf-out and development of understory vegetation). Thus, any variation in frontal fire intensity is primarily due to changes in forward rate of fire spread, as determined by the MC of fine dead surface fuels and wind velocity.

The computed frontal fire intensities, observed flame heights, and the 1.4-m stand wind speeds measured in the present study compare very favorably with the empirical relationships derived by Nelson and Adkins (1986). Flame depths were not formally documented during this study, and it is therefore not possible to compute residence times (Merrill and Alexander 1987), i.e., the length of time required for the flaming zone or fire front of a spreading fire to pass a given point (cf. Alexander 1982a):

$$[5] \quad t_R = \frac{D}{r}$$

where, t_R = residence time (min), D = flame depth (m), and r = linear rate of fire spread (m/min). In the operational prescribed fire documented by Kiil (1970), the depth of the active flaming zone of the head fire was determined to be 0.6 m; therefore, the computed residence time would have been 0.16 min or about 10 sec. Photographs taken of the 1972 fires (Fig. 7) and examination of the head fire ROS values listed in Table 4 would suggest similar residence times for those head fires. Further evidence supporting this statement is provided by the empirical relationship—derived by Nelson and Adkins (1988)—between rate of fire spread, fuel consumption, wind speed, and residence time.

The ISI-ROS relationships represented by eqs. [1], [2], and [3] are for an equilibrium or "steady-state" condition on level-to-gently-undulating terrain. For fires spreading upslope or downslope, ROS predictions require adjustment for the mechanical effects of slope steepness on the fire spread rate (Van Wagner 1977a, 1988; McAlpine et al. 1991). Fires occurring in leafless aspen stands

during the fall actually tend to exhibit higher spread rates than predicted: this is due to the short-range spotting caused by wind-tumbled leaves (those that have had sufficient time to "cure") being rolled or blown ahead of the advancing fire front (Anderson 1982). According to the Beaufort wind scale (Turner and Lawson 1978), this kind of short-range spotting is probable when 10-m open wind speeds are in excess of 15–20 km/h.

Although a fire's forward ROS on level terrain is mainly dependent on wind speed and fine fuel MC (as currently represented by the ISI component of the FWI System), it is undoubtedly true that the spread rate of an established, free-burning fire is also influenced to a certain degree by the amount of available heavy fuel. For leafless aspen stands, Van Wagner (1973) has suggested that an increased spread rate would take place at a BUI of around 40; at BUI levels of 60 and 80, the expected increase in head fire ROS would be 4% and 7%, respectively. (Similar adjustments have been incorporated into the Canadian Forest Fire Behavior Prediction System [Forestry Canada Fire Danger Group 1991]).

Brown and Simmerman (1986) compared the predictions from their fire behavior guide for western U.S. aspen stands with the results of four test fires. Three of these four fires failed to spread as predicted. In the fire that did sustain itself, there was good agreement between predicted and observed flame lengths. Some indication is presented in Table 7 of the relative accuracy of predicting head fire ROS in the leafless aspen fuel type, using any one of the three ISI-ROS equations shown in Figure 8. When reviewing the results, it should be noted that the stand and fuel characteristics for those fires would not have been exactly the same as for the present study. Also, except for the two 1983 experimental fires, wind speed was measured at some distance (~5–10 km) from the fire site, usually at 1200 local standard time, which would not necessarily coincide exactly with the ROS observation(s) in Table 7.

Fire spread in forest fuels has generally been regarded as an approximate exponential function of wind speed. Cheney (1985) indicated that a power function might be more appropriate, although a simple exponential usually allowed a reasonable fit of the data, as well. A power function has been employed in other ISI-ROS relationships in forest stands (e.g., Van Wagner 1973; Quintilio et al. 1977). The linear function appears to be most

Table 7. Predicted head fire rate of spread, based on the three equations derived from the results of the present study, versus the observed values documented during six experimental and operational prescribed fires in leafless aspen stands

Source or reference	Date of burning	Geographical location of fire area[a]	Initial Spread Index (ISI)	Observed head fire ROS[b] (m/min)	Predicted head fire ROS		
					Linear (Eq. [1])	Exponential (Eq. [2])	Power (Eq. [3])
Dubé, unpubl.[c]	28.04.80	Elk Is. NP, Alta.	9	2.29	1.14	0.95	1.02
Johnston (1981)[d]	05.05.80	Elk Is. NP, Alta.	4	0.25-0.50	0.34	0.43	0.44
Dubé, unpubl.[c]	12.05.82	Elk Is. NP, Alta.	5	0.61	0.50	0.50	0.56
Delisle, unpubl.[e]	29.04.83	Elk Is. NP, Alta.	11	0.75	1.46	1.31	1.25
Delisle, unpubl.[e]	11.05.83	Elk Is. NP, Alta.	13	1.28	1.78	1.81	1.48
Hirsch, unpubl.[f]	07.10.88	Duck Mtn., Man.	4	0.25-1.0	0.34	0.43	0.44

[a] Fire areas: Elk Is. NP, Alta. = Elk Island National Park, Alberta; Duck Mtn., Man. = Duck Mountain, Manitoba.

[b] ROS = Rate of spread.

[c] Unpublished data collected by D.E. Dubé is on file with the Fire Management Research Project at Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

[d] See also Johnston and Woodard (1985).

[e] Unpublished data collected by G.P. Delisle is on file with the Fire Management Research Project at Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

[f] Personal communication from K.G. Hirsch, Fire Research Officer, Forestry Canada, Northwest Region, Manitoba District Office, Winnipeg, Manitoba.

appropriate for fuel complexes with only one distinct layer, such as logging slash (e.g., Quintilio 1972). The correct relationship becomes critical for extrapolation beyond the range of the data (Cheney 1985). In order to establish a more definitive guide to the prediction of fire spread, additional observations are needed, particularly for more extreme burning conditions with stronger winds. Such data is most likely to be obtained from a few well-documented wildfires (e.g., Stocks 1988), rather than from the analysis of a vast number of individual forest fire reports (Walker 1971). However, it is expected that additional data will prove fire spread begins to level off at very high ISI values (Stocks 1989).

The ISI component of the FWI System combines the effects of fine fuel moisture (represented by the FFMC) and wind on the rate of fire spread. In the present study, all but one fire was conducted with an FFMC of between 91 and 93, which indicated relatively little variation in fine fuel MC. The derived ISI-ROS relationships were able to account for only about 50% of the observed variation in head fire ROS, which is considerably less than for natural conifer stands or for logging slash resulting from the clear-cutting of these forests (Quintilio 1972; Quintilio et al. 1977; Stocks 1989). This would suggest that the FFMC as it is now formulated may not be the most appropriate indicator of the MC of litter and other cured fine fuels in leafless aspen stands, although higher correlations between forward rate of fire spread and the ISI have been reported for leafless aspen—northern hardwood fuel types (but for a smaller number of experimental fires and a greater range in observed ROS [Alexander and Sando 1989; Sando and Alexander 1990]). The development of the FFMC was based on fuel moisture studies using shaded pine needle litter (Van Wagner 1987), which is known to exhibit different drying and wetting characteristics than weathered aspen leaves (Van Wagner 1969b, 1972a). Modifications to the FFMC (e.g., changes to the equilibrium moisture content to account for the effects of isolation) or the development of a fuel-specific moisture code for the litter layer in leafless aspen stands could reduce the observed variation in head fire ROS experienced in this study. Two separate moisture codes may, in fact, be required for the spring and the fall because of obvious differences in the chemical composition (e.g., waxy cuticle) and physical arrangement (e.g., bulk density) of fallen aspen leaves in the spring and fall (Van Wagner 1969b, Crosby and Loomis 1974; Brown and Simmerman 1986). Such specialized moisture code(s) would fit within the role envisaged for the Accessory Fuel Moisture System of the CFFDRS (Stocks et al. 1989).

Perhaps it is unrealistic to expect a very high degree of correlation between fire danger indexes and fire characteristics at the low end of the fire behavior scale. When this study's 1972 results (covering a small range in fire spread and intensity) are assessed as part of a broad range of fire behavior, then the variations are less apparent between head fire ROS and the ISI.

Are natural, trembling aspen fuel complexes capable of exhibiting characteristics of extreme fire behavior—such as, for example, extremely fast-spreading surface fires (>25 m/min) that have frontal intensities of >10 000 kW/m and significant spotting distances? The answer is yes, but it applies only to severe burning conditions in the spring (Kiil and Grigel 1969; Bailey 1978a; Simard et al. 1983). For example, one documented wildfire not included in Figure 9 is the Little Sioux Fire in northeastern Minnesota (Sando and Haines 1972), which made its major run on May 14, 1971. The 1300 local daylight time observations at the nearest fire weather station were, as adapted from Sando and Haines (1972), as follows: dry-bulb temperature of 24.4°C; RH of 15%; 10-m open wind spread of 30 km/h; 10 days after ≥ 0.6 mm of rain; FFMC of 95; DMC of 45; DC of 93; ISI of 40; BUI of 45; and FWI of 53 (Alexander and Sando 1989). The frontal fire intensity experienced in one aspen-dominated stand was estimated to have been approximately 13 000 kW/m (Ohmann and Grigal 1979). In such instances, it appears as if a crown fire is occurring in the leafless aspen forest because of the associated flame heights; some fine dead crown fuel will be consumed by such a high-intensity surface fire. However, "aspen do not crown" (Van Wagner 1977b) in the same sense as conifer forests (i.e., a fire ascends into the crowns of trees and/or spreads from crown to crown), except, perhaps, under very severe burning conditions preceeded by extreme drought in the fall (Fahnestock 1970; Sando and Wick 1972; Rowe and Scotter 1973). These conditions occurred in northern hardwoods before and during the Bar Harbor Fire in Maine, on October 23, 1947 (Wilkins 1948; Haines et al. 1976). Weather conditions, both previous and current, do not have to be quite so severe when the fuels in a stand have

been disturbed by herbicides (*see* Wright and Bailey 1982, p. 428, Fig. 16.33), cutting, or a recent fire.

An incident that occurred on April 28, 1988, at Elk Island National Park[3] in central Alberta serves to illustrate the fact that extreme fire behavior can occur in the aspen fuel type during the leafless stage in the spring with a moderate air temperature (22.5°C), low RH (14%) but light winds (~10 km/h), 8 days after ≥ 0.6 mm of rain. Slope steepness (20%), aspect (southerly exposure), low fuel moisture levels (FFMC of 94, and BUI of 71), and a very unstable atmosphere contributed to an observed head fire ROS of 30 m/min and flame heights exceeding 10 m.

The importance of stem diameter and some direct or indirect measure of frontal fire intensity with respect to tree survival following fire has been well-substantiated (Wade 1987; Ryan 1990). Although quantitative models for predicting fire-caused tree mortality have been produced (e.g., Simard and Baumgartner 1986; Brown and DeByle 1987; Ryan 1990), these models, however, are not appropriate to the present study for a variety of reasons (e.g., inapplicability to trembling aspen and/or incompatability of inputs/outputs). Brown (1985a) initially reported that to consistently kill aspen required flame lengths of 0.4 m, or a frontal fire intensity of 35 kW/m, according to Byram's flame length–fire intensity formula (cf. Alexander 1982a). This general guideline was later revised by Brown and Simmerman (1986) to 0.52–0.64-m flame lengths (or frontal fire intensities of 62–97 kW/m). Although in neither case was the dbh size class specified, this latter rule of thumb is in agreement with results from the present study.

After a fire, vigorous aspen regeneration by prolific root suckering is normal, due to the combined effect of two conditions: the reduction of apical dominance to a minimum (i.e., the parent tree is top-killed) (Schier 1985); and increased soil temperatures (Maini and Horton 1966a; Hungerford 1988). Aspen suckering was insignificant, however, following the 1972 burns and the 1978 reburn; the absence of prolific suckering after the 1972 series of experimental fires was unexpected. Three conditions may explain the almost total lack of aspen regeneration following all the burning:

1. the rooting zone remained cool after the fires as a result of initial temperature (0°C) and a moist duff layer;

2. the trees on all plots leafed out, which indicated that sap flow had been initiated before and during the burning period; and

3. although fire-induced tree mortality became evident during the first growing season, root carbohydrate reserves may have been inadequate to promote suckering so late in the growing season (Harrington 1989).

Weber (1990a, 1990b, 1991a, 1991b) recently completed a study in eastern Ontario that tends to support this explanation: he compared the effects of the cutting and burning of immature aspen before and after vernal leaf flushing, and he found, as expected, that cutting before leaf flush produces much stronger root suckering than postflush cutting. With respect to burning, this effect was overshadowed by the effect of frontal fire intensity. Intense surface fires killed the trees outright and resulted in strong suckering, but gentle surface fires only girdled the trees; they died a year or two later after exhausting their root reserves, leaving relatively few suckers.

CONCLUSIONS

The literature on the ecology and management of trembling aspen, which includes a component on fire, is extensive (Maini and Cayford 1968; Shoup et al. 1968; United States Department of Agriculture, Forest Service 1972; Brinkman and Roe 1975; Perala 1977; DeByle 1981; Capp and Gadt 1984; DeByle and Winokur 1985; Davidson et al. 1989). However, in comparison to the other kinds of information available on trembling aspen, there is an almost complete lack of empirical fire behavior data in

[3] Deering, P. 1988. Extreme fire behavior observed during the 1988 Shirley Lake prescribed fire. Canadian Parks Service, Elk Island National Park, Warden Service, Fort Saskatchewan, Alberta. Unpublished report.

relation to documented burning conditions. This study provides information on head fire ROS, fuel consumption, and frontal fire intensity that contributes to the understanding of fire behavior in the boreal forest, especially with regard to fire impact and effect on aspen ecosystems. In addition, the data has also proved valuable in other fire research studies in Alberta (Quintilio and Anderson 1976) and elsewhere (Martell et al. 1984). The results obtained from this study have been combined with those of other experimental fires in east-central Canada (Van Wagner 1973, 1975; Weber 1990b), western Canada (Kiil 1970), and the Lake States region of the U.S. (Alexander 1982c; Alexander and Sando 1989) as well as a few well-documented wildfires (Van Wagner 1965) to produce ISI-ROS relationships for the leafless aspen (D-1) and boreal mixedwood-leafless (M-1) fuel types in the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985; Forestry Canada Fire Danger Group 1991).[4] The FBP System is used by fire management agencies and other fire researchers throughout Canada. Also, the additional knowledge gained on certain fire effects in relation to quantified fire impact and behavior will contribute to improved computer simulations (Methven and Feunekes 1988) and burning prescriptions (Sando and Alexander 1990) with respect to the use of prescribed fire for trembling aspen vegetation management (Corns 1989).

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Alberta Forest Service, whose members conducted the experimental fires. From Forestry Canada, Northwest Region, M.W. Walters, formerly Northern Forestry Centre (NoFC) Fire Research Technician, and M.E. Maffey, NoFC Fire Research Technician, were responsible for some of the vegetation and surface fuel sampling, and assisted with the data processing. D.E. Dubé, former NoFC Fire Research Project Leader, and R.J. Lieskovsky and R.G. Gordy, formerly NoFC Fire Research Technicians, assisted with the May 1978 reburn and Z. Chrosiewicz, NoFC Research Scientist (now retired), provided daily fire weather observations throughout the study period in 1978. B.J. Stocks (Ontario Region, Great Lakes Forestry Centre), M.G. Weber and C.E. Van Wagner (Petawawa National Forestry Institute), T.B. Williamson (NoFC), all with Forestry Canada, provided many useful comments on a review draft of this report. The efforts of M.S. Mason, NoFC Scientific Editor, greatly improved the final product.

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APPENDIX

DAILY FIRE WEATHER OBSERVATIONS RECORDED AT 1200 MST OR 1300 MDT

Table A. Data recorded at Chisholm lookout tower, May 1-15, 1972 (station elevation: 677 m MSL)

Calendar date (1972)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	24-hour rain (mm)
May 1	11.7	24	5	0.0
2	13.9	29	6	0.0
3	11.7	54	13	0.0
4	10.6	47	14	3.0
5	3.3	92	0	10.9
6	8.9	38	5	6.3
7	12.2	30	11	0.0
8	14.4	30	13	0.0
9	17.2	28	11	0.0
10	17.2	32	14	0.0
11	19.4	25	5	0.0
12	17.2	40	18	0.0
13	20.6	34	18	0.0
14	16.7	27	11	0.0
15	11.7	39	8	0.0

Table B. Data recorded at a temporary fire weather station, April 24-May 5, 1978 (station elevation: 595 m MSL)[a]

Calendar date (1978)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	24-hour rain (mm)
April 24	11.5	58	5	0.0
25	17.5	28	3	0.0
26	21.5	26	8	0.0
27	21.5	29	7	0.0
28	20.5	33	9	0.0
29	15.5	47	14	10.4
30	17.0	34	11	0.0
May 1	15.0	42	7	0.0
2	14.0	48	11	0.5
3	12.5	29	17	0.0
4	13.0	30	9	0.0
5	14.5	25	9	0.0

[a] Personal communication from Z. Chrosciewicz, Research Scientist, Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

Table C. Data recorded at Heart Lake lookout tower, April 23-May 16, 1969 (station elevation: 887 m MSL)

Calendar date (1969)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	24-hour rain (mm)
April 23	12.2	37	19	0.0
24	10.0	59	21	1.3
25	0.6	100	11	10.9
26	-0.6	100	6	2.0
27	0.0	100	8	0.0
28	10.6	53	6	0.0
29	12.8	38	11	0.0
30	12.2	41	6	0.0
May 1	15.0	33	14	0.0
2	8.9	46	5	0.0
3	7.8	49	8	13.0
4	8.3	75	10	0.0
5	8.9	63	21	0.8
6	5.0	63	11	1.3
7	10.0	43	10	0.0
8	17.8	21	13	0.0
9	11.7	40	26	0.0
10	12.8	34	8	0.0
11	14.4	32	16	0.0
12	17.8	31	11	0.0
13	17.8	38	10	0.0
14	3.9	70	16	0.0
15	6.7	36	6	0.0
16	10.6	33	14	0.0